Improvements to Passive Acoustic Tracking Methods for Marine Mammal Monitoring

Eva-Marie Nosal
Department of Ocean and Resources Engineering
University of Hawaii at Manoa
2540 Dole Street
Holmes Hall 405
Honolulu, HI 96822, USA
phone: (808) 956-7686 fax: (808) 956-3498 email: nosal@hawaii.edu

Award Number: N000141210206
http://www.soest.hawaii.edu/ore/faculty/nosal

LONG-TERM GOALS

The long-term goal of this project is to improve model-based passive acoustic methods for tracking marine mammals. When possible, tracking results are used to study marine mammal behavior and bioacoustics.

OBJECTIVES

The first three objectives of this project are to investigate and implement several specific ideas that have the potential to improve the accuracy, efficiency, and applicability of model-based passive acoustic tracking methods for marine mammals:

1) Invert for sound speed profiles, hydrophone position and hydrophone timing offset in addition to animal position.
2) Improve maximization schemes used in model-based tracking.
3) Use information in addition to arrival times for tracking.

The final objective of this project is to:

4) Improve and test approaches to simultaneously track multiple animals simultaneously in cases where it is difficult/impossible to separate and associate calls from individual animals.

APPROACH

Eva-Marie Nosal is the key individual participating in this work as the principal investigator and main researcher.

This project uses existing datasets. The main effort is directed toward data collected at Navy Ranges, with data from PMRF provided by S. Martin and data from AUTEC provided by D. Moretti. Other

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **2012**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Improvements to Passive Acoustic Tracking Methods for Marine Mammal Monitoring**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Department of Ocean and Resources Engineering University of Hawaii at Manoa 2540 Dole Street Holmes Hall 405 Honolulu, HI 96822, USA**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

datasets that use bottom-mounted sensors are also be considered if available and appropriate. The main species of interest in these datasets are sperm whales, beaked whales, minke whales, and humpback whales. Most methods developed will be generalizable to other species.

This project uses model-based tracking methods [e.g. Tiemann et al. 2004; Thode 2005; Nosal 2007] the have been developed to localize animals in situations where straight-line propagation assumptions made by conventional marine mammal tracking methods fail or result in unacceptably large errors. In the model-based approach, a source is localized by finding the position that gives predicted arrival times that best match the measured arrival times. This is done by creating a likelihood surface that gives the probability of an animal at any position in space. The maxima of this surface give the estimated animal position(s). Arrival time predictions are made using a sound propagation model, which in turn uses information about the environment including sound speed profiles and bathymetry. Calculations are based on measured time-of-arrivals (TOAs) or time-differences-of-arrival (TDOAs), modeled TOAs/TODAs, estimated uncertainties, and any available a priori information. All methods are fully automated through MATLAB code.

The approaches taken for each of the objectives are further expanded separately below:

Objective 1: <u>Invert for sound speed profiles, hydrophone position and hydrophone timing offset in addition to animal position</u>
Almost all marine mammal tracking methods treat animal position as the only unknown model parameter. Other parameters (sound speed, hydrophone position, hydrophone timing) are treated as known inputs and estimated error in these “knowns” is propagated to give error in estimated animal position. This is not always the best approach since it can cause location errors to become unnecessarily large. Moreover, small offsets in hydrophone timing lead to entirely incorrect position estimates (and unfortunately timing is a serious practical problem for passive acoustic tracking systems that comes up repeatedly in real-world datasets). Moreover, there are situations in which sound speeds, phone position and/or timing offsets are entirely unknown.

Sound speed, phone position and/or timing offsets can be readily be included in the set of unknown model parameters in model-based tracking, with any known information incorporated as *a priori* information. This approach has potential to yield much improved position estimates and/or to give position estimates in cases that would be otherwise impossible. This approach has been used successfully by the underwater acoustics community [e.g. Collins and Kuperman, 1991; Fialkowski et al. 1997; Tollefsen and Dosso, 2009] but modifications for and application to marine mammal tracking remains limited [but see Thode 2000].

Objective 2: <u>Improve maximization schemes used in model-based tracking</u>
In past model-based localization work, likelihood surface maximization has usually been implemented using a grid search (sometimes using multiple-step approach starting with coarse grids that are successively refined). This part of the project investigates the benefit of implementing more sophisticated maximization schemes to find local maxima in the likelihood surfaces. Potential benefits of using these schemes include reduced run times and more precise position estimates. In addition, one serious drawback of the approach from Objective 1 (increased parameter space) is increased computational complexity due to larger search spaces; using more sophisticated maximization schemes is critical in keeping the problem computationally viable.

Objective 3: Use information in addition to arrival times for tracking
Almost all marine mammal tracking methods rely solely on arrival times. There is often additional information that changes with animal position and can consequently be used to obtain/improve position estimates. Several researchers have used sound pressure level or propagation characteristics for tracking [e.g. Cato 1998; McDonald and Fox 1999; McDonald and Moore 2002; Wiggins et al. 2004]. Past approaches have generally been limited to assumptions of omni-directional sources and spherical spreading; assumptions that do not always apply. With some modification, the model-based localization methods used in this project can incorporate source levels and transmission loss and account for confounding factors such as source directionality (e.g. by including animal orientation and beam pattern in the inversion process). These modifications will be made to investigate the feasibility of incorporating received levels in tracking methods.

Objective 4: Multiple animal tracking
One approach taken to track multiple animals involves developing source separation methods that are applied prior to tracking. Once sources have been separated on each hydrophone, the association problem (identifying the same call on all hydrophones) is greatly simplified. If multiple animals can thus be separated and calls associated, the problem is reduced to multiple applications of single-animal tracking methods.

Different approaches for multiple animal tracking are being explored for cases in which source separation/association is not possible. One possibility is to use the model-based tracking framework and include all possible associations (or cross-correlation peaks) in the likelihood surfaces. This approach requires the maximization method from Objective 2.

WORK COMPLETED

Objective 1: A preliminary effort to test and demonstrate the usefulness of inverting for sound speed profile (SSP) in addition to animal position focused minke whale boings at PMRF (7 hydrophone localization dataset from the 2011 Workshop on Detection, Classification and Localization (DCL) of Marine Mammals). The animals were expected to be relatively close to the surface (since baleen whales are generally not deep divers). Since sound speed varies most near the surface (due to heating/cooling and mixing effects), the effect of sound speed profile (SSP) uncertainty was expected to be of some significance in this case. Sound speed was assumed to vary with depth but not with range or time. Principal component analysis of monthly historical SSPs was used to reduce the dimensionality of the SSP space. Figure 1 shows the first 3 principal components of the variance of SSP from the mean (over all monthly profiles). In the inversion, SSP was modeled as the mean SSP over all months plus a linear combination of the first 3 principal components (retaining those characteristics that contribute most to SSP variance and ignoring the higher-order components). Inversion for SSP was applied globally over all localized calls.

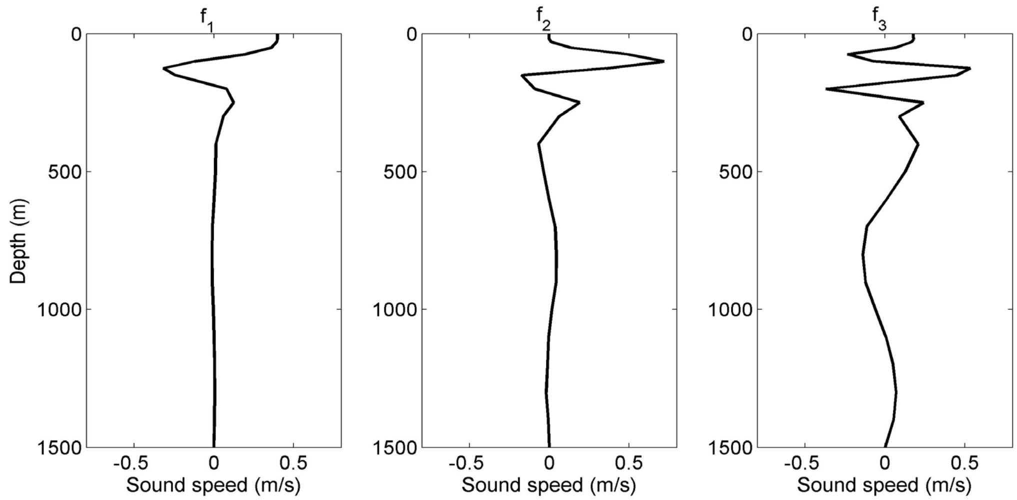

Figure 1. First 3 principal components of the variance of SSP from the mean over monthly historical data.

Objective 2: A simple downhill simplex optimization scheme (Neadler-Meade) was implemented for the PMRF minke whale dataset. The optimization scheme consistently converged to value near the correct maxima and overall run times were reduced by ~10 times when compared with a grid-search method (which successively refines grid spacing as the algorithm "zooms in" on the final solution). The same approach was applied to the AUTEC sperm whale localization datasets from the 2005 DCL Workshop and worked well in cases with relatively simple likelihood surfaces (i.e. small parameter spaces and few peaks from few animals and well-associated calls) [Nosal, accepted]. Numerous improvements and refinements must still be made to understand issues such as: relative advantages/disadvantages of different optimization schemes; strategies for dealing with multiple likelihood surface peaks (as from multiple animals or spurious peaks).

Objective 3: None to report at this time

Objective 4: Theory was developed for a method that extends model-based tracking to cases with multiple animals and/or cases where call association and/or classification are difficult/impossible. The method results in a multi-modal likelihood surface in which persistent peaks are tracked over time to estimate produce animal locations/tracks. The method was thoroughly tested on simulated data and applied to the AUTEC multiple sperm whale dataset. A full description of the method is beyond the scope of this report, but has been accepted for publication in the Journal of the Acoustical Society of America [Nosal, accepted]. Figure 2 illustrates the approach for a case with 2 animals.

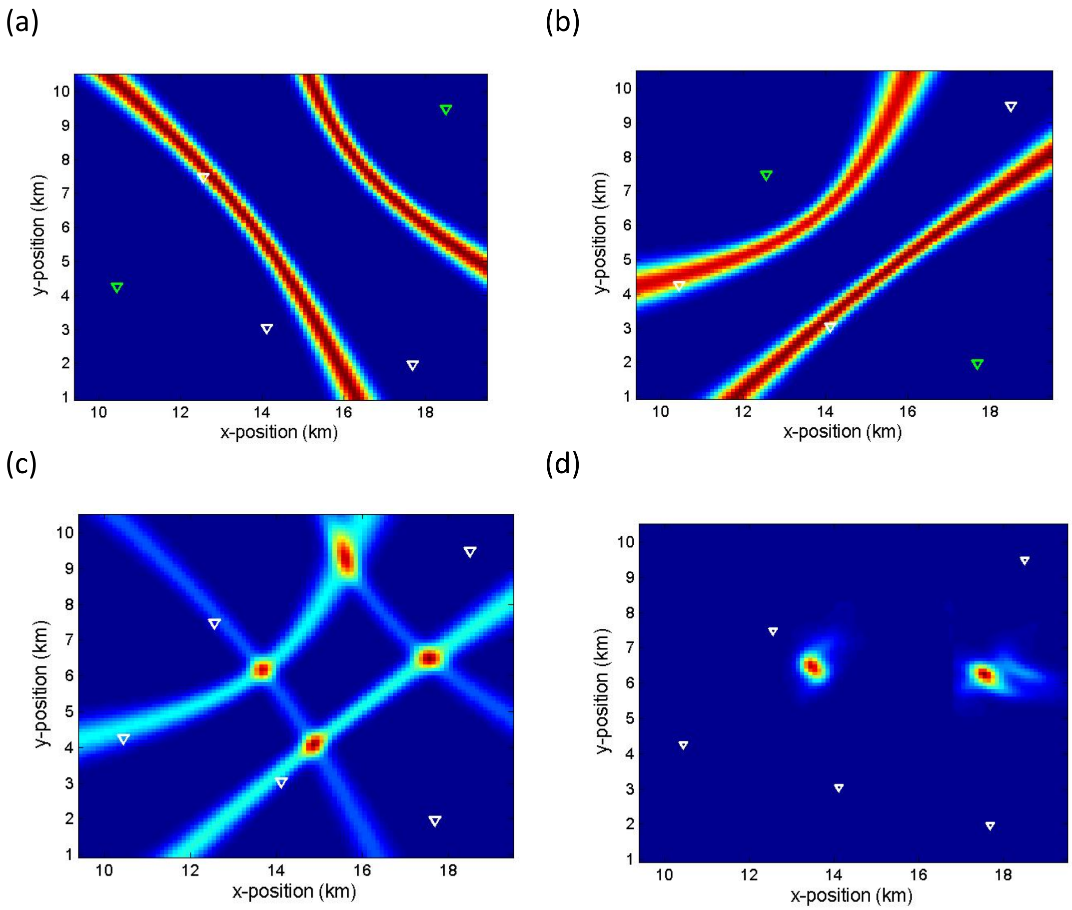

Figure 2 (a) For the hydrophones (triangles) shown in green, a likelihood surface (red/blue indicate high/low probability of source presence) is created that incorporates all possible TDOAs (in this case 2). (b) A different pair hydrophones results in a second likelihood surface. (c) Surfaces from (a) and (b) are multiplied to give 4 possible source locations. (d) Combining likelihood surfaces from all receiver pairs reveals the 2 correct source positions. No source separation or association was required.

RESULTS

Objective 1: Including SSP in inversions resulted in “tighter” peaks in the localization likelihood surfaces since data and model were better matched by including inversion for SSP in the process. In the dataset considered, this reduced 95% confidence intervals in position estimates by 2-5 times. Additional work in this direction on is ongoing.

Objective 2: In relatively simple cases (e.g. single animal, well-associated calls) the model-based likelihood surfaces have single peaks. In these cases, simple optimization schemes work efficiently and well and can significantly improve run-times (a 10 times improvement was seen, but improvement will vary on a case-by-case basis and depending on the details of each implementation). In more complicated cases (e.g. multiple animals and/or mis/un-associated calls) the likelihood surfaces are multi-modal and require more sophisticated optimization schemes to identify maxima. Work on these is ongoing.

Objective 3: None at this time

Objective 4: The model-based TDOA method was extended to deal with multiple-animal datasets using a method in which animals are separated based on position. The method does not require a TDOA association step, and false TDOAs (e.g. a direct path associated with a multipath arrival) do not need to be removed. An analogous development was also made for a model based time of arrival (TOA) tracking method. Both methods are outlined in Nosal [accepted].

IMPACT/APPLICATIONS

The localization and tracking methods developed in this project are useful for monitoring and studying marine mammal bioacoustics and behavior in the wild. Tracking results can be used to establish detection ranges and calling rates that are critical in density estimation applications. Methods developed to track marine mammals are useful for sources other than marine mammals (e.g. tracking of surface vessels can help to monitor fishing efforts in marine protected areas).

RELATED PROJECTS

NSF award 1017775. Signal Processing Methods for Passive Acoustic Monitoring of Marine Mammals. (PI: E-M Nosal, Co PI: A Host-Madsen). Application of signal processing methods from speech and communications to passive acoustic monitoring of marine mammals. Focuses on detection and classification instead of on localization (this project). Progress made in this project directly benefits the proposed project (and vice versa).

ONR (Ocean Acoustics) N000141010334. Acoustic Seaglider: Philippine Sea Experiment (PI: B Howe, CoPI: E-M Nosal, G Carter, L VanUffelen). Use of gliders to record transmissions in the PhilSea10 tomography experiment. Some of the inverse methods used share similar theory and implementation. In the PhilSea project, the "unknown" of interest is sound speed (hence temperature and salinity) while in this project it is source location.

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PUBLICATIONS

Papers

Nosal, E-M (accepted). Methods for tracking multiple marine mammals with wide-baseline passive acoustic arrays. *J. Acoust. Soc. Am*. [refereed].

Conference abstracts

Nosal, E-M (2012). Tracking multiple marine mammals using widely-spaced hydrophones. Acoustics Week in Canada, Banff, AB. 10-12 Oct, 2012.